

# 1 The Atmospheric Neutrino Anomaly: Muon Neutrino Disappearance

John G. Learned

## 1.1 Introduction

With the 1998 announcement of new evidence for muon neutrino disappearance observed by the Super-Kamiokande experiment, the more than a decade old atmospheric neutrino anomaly moved from a possible indication for neutrino oscillations to an almost inescapable implication. In this chapter the evidence is reviewed, and indications are presented that the oscillations are probably between muon and tau neutrinos with maximal mixing. Implications and future directions are discussed.

The understanding of this phenomenon is now dominated by the data announced by the Super-Kamiokande Collaboration at Neutrino98, of which group the present author is a member. Much of this report dwells upon those results and updates to them, and so credit for this work is due to the whole Collaboration, listed in the Appendix, who have labored hard to bring this experiment to fruition and who have been ably led by Prof. Yoji Totsuka of the University of Tokyo. That said, this report presents personal recollections and opinions of the author, particularly in matters of the previous history, interpretation of the present situation, and future prospects for this line of research.

The phenomenon of neutrino oscillations is discussed in several other Chapters of this volume (II and IX in particular), and to those the reader is directed for derivation of the expressions utilized in this Chapter and for understanding of the origin and implications of neutrino oscillations generally. Model building and implications in astrophysics and cosmology are likewise treated elsewhere, while in the following we focus narrowly upon the atmospheric neutrino anomaly, its experimental explication in terms of muon neutrino oscillations with tau neutrinos, and the implications of those results.

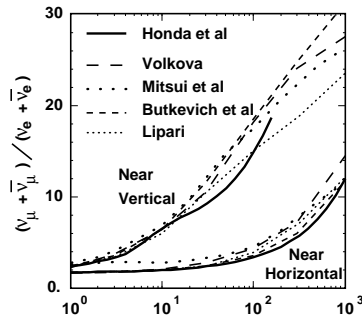
### 1.1.1 Atmospheric Neutrinos

The neutrinos under discussion in this chapter arise from the decay of pions and other mesons, and muons, which are produced in the earth's atmosphere[1,2]. The atmosphere is being constantly bombarded with cosmic rays, which consist mostly of protons, but also heavy nuclei and electrons, and even neutral particles. The earth's magnetic field, plus other magnetic fields cut off the

lower energy particles from the sun and more distant sources, so that the mean incoming kinetic energy is around 1 *GeV*. Cosmic rays with lower energies do not cause effects which we can directly detect on earth or underground. Particles with energies in the multi-GeV range make showers in the roughly ten-interaction-length-thick (vertical column density) atmosphere. Cosmic ray collisions with air nuclei produce pions and other particles in abundance, which themselves further interact or decay. This competition between interaction and decay leads to a steeper spectrum for the decay products. At energies below several GeV the muons produced in charged pion decay, themselves decay:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \quad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu, \quad (1.1)$$

with decay lengths of  $L_{\pi^\pm} = 0.056 \text{ km} \times E_\pi/\text{GeV}$  and  $L_\mu = 6.23 \text{ km} \times E_\mu/\text{GeV}$ . Typical pion interaction lengths (roughly 150 *gm/cm*<sup>2</sup>) are on the order of a few *km* depending upon altitude, angle and energy, while muons generally come to rest before decaying or being absorbed. Moreover (crucially and often ignored) the energy sharing in the decays is such that the resulting neutrinos are also of nearly equal energy. These decay kinematics are of course well known, so the ratio of muon neutrinos to electron neutrinos can be calculated with rather good accuracy, about 5%, almost independently of the cosmic ray spectrum[3,5], as illustrated in Figure 1.1.



**Fig. 1.1.** The calculated ratio of the fluxes of atmospheric muon neutrinos to electron neutrinos, versus neutrino energy. Figure from Honda[7].

Precise neutrino flux calculations (few percent) from man-made sources are difficult if not impossible, as indicated in other chapters in this book. The problem is even more difficult for the atmospheric neutrinos, since the absolute magnitude of the incoming cosmic ray flux is not well known, being uncertain at present to perhaps 25%. [3]. The calculations of the atmospheric neutrino flux in the few *GeV* energy range require not only the input cosmic ray flux, with appropriate modulation to account for solar cycle variation and geomagnetic field, but also details of nucleon-nucleon and meson-nucleon

interactions, not all of which have been well measured. The neutrino flux calculations also lead to *muon* flux predictions, and these can be (and have been) compared to data, though the appropriate data for low energy muons at high altitude, as recorded in balloon measurements, is sparse and imprecise. Typically these calculations incorporate the approximation that the incoming cosmic rays, the secondaries and even the neutrinos all travel in the same direction. This is no doubt not a serious compromise in the few *GeV* energy range, but has some effects in the energy range of a few hundred *MeV*. At this time new calculations are in progress[8], but the computer time required to do the full simulation is still a limiting factor and the job has yet to be done definitively.

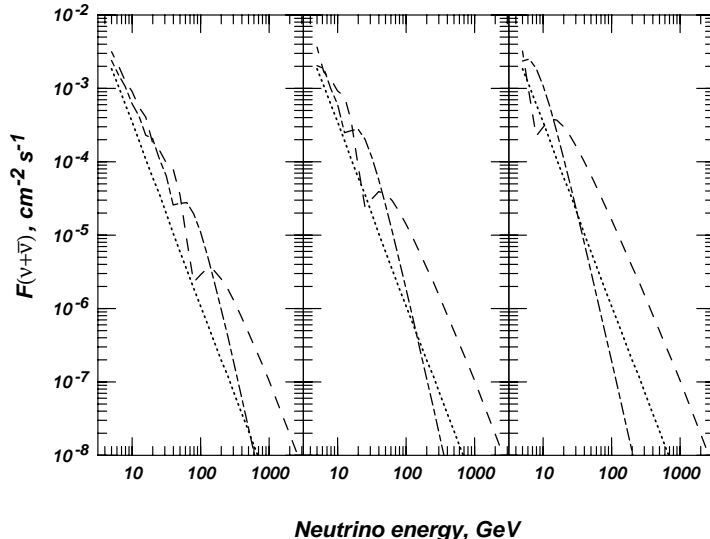
Several features of the neutrino flux are worth mentioning. The muon neutrino flux can be approximated as a power law with spectral index  $\gamma \simeq -3.7$ [7] for energies between about 10 *GeV* and 100 *TeV*. The electron neutrino (and anti-neutrino) fluxes which largely arise from muon decay, fall off more swiftly above several *GeV*, with strong angle dependence. As illustrated in Figure 1.1 the  $\nu_\mu$  to  $\nu_e$  flux ratio falls to a few percent at the higher energies, where the  $\nu_e$ 's are mostly produced in kaon decay,  $K^+ \rightarrow \pi^0 e^+ \nu_e$  (4.82% BR). See Figure 1.2 for atmospheric neutrino spectra of all three flavors, as expected under several assumptions of oscillations (two-flavor oscillations only).

There is a significant zenith angle variation in the atmospheric neutrino flux, more prominent at higher energies, called the “secant theta” effect. This is simply due to the fact that those pions and muons which are produced by incoming cosmic rays with trajectories nearly tangential to the earth have more flight time in less dense atmosphere, and hence more chance to decay. Thus there is a peak, becoming more prominent at higher energies, near the horizontal arrival direction in the atmospheric neutrino angular distribution. This peak is symmetric about the horizon for any location except at the lowest neutrino energies, below around 400 *MeV*, where geomagnetic effects spoil the symmetry somewhat.

The atmospheric neutrino energies practically accessible in underground experiments range from the few tens of *MeV* to the 1 *TeV* range, and the flight distances from roughly 20 *km* for down-coming neutrinos to 13,000 *km* for those traversing the earth from the far side. The neutrino cross section is sufficiently small that there should be negligible attenuation of these neutrinos: the attenuation is roughly  $2.4 \times 10^{-5} E_\nu / \text{GeV}$  for neutrinos traversing the earth's core, and thus negligible for any energies below about 100 *TeV*. In consequence of the large dynamic range in both energy and flight distance, the atmospheric neutrinos are potentially sensitive to oscillations over a range of mass squared differences from about  $10^{-4}$  to  $10^{-1} \text{ eV}^2$ , as is discussed below.

### 1.1.2 Initial Indications

We will not dwell upon the past history[9], but note that the atmospheric neutrino anomaly has been around for some time, roughly since the mid-1980's.



**Fig. 1.2.** Neutrino fluxes of all three flavors (dots:  $\nu_e$ , dashes:  $\nu_\mu$ ), long-short dashes  $\nu_\tau$ .) in the presence of  $\nu_\mu \rightarrow \nu_\tau$  oscillations with maximal mixing and  $\Delta m^2 = 10^{-2}, 10^{-2.5}, 10^{-3} \text{ eV}^2$ , from left to right. Figure from Staney[3].

Indeed the first notice of something peculiar in the atmospheric neutrino data stems from the 1960's when the seminal underground experiments in South Africa[10] and South India[11] first detected the natural neutrinos and observed somewhat of an absolute rate deficit, but not convincingly as the flux predictions were rough and the statistics small.

A new round of instruments were built beginning in the late 1970's to search for nucleon decay as predicted by the (soon to be discarded) SU(5) unification model. The problem with atmospheric neutrinos, a background to nucleon decay searches, became serious after the activation of the first large water underground Cherenkov detector, the IMB experiment, and by 1983 the realization that the number of events containing muon decays was less than expected[12]. Soon this was confirmed by the second large water detector, the Kamioka experiment[13], which group extended the results with good particle identification giving a redundant measure of the relative muon deficit (as also did IMB). Some members of the IMB[14] and the Kamioka[15] groups began to suggest, at least in private, that oscillations were the cause of the deficit, but that conclusion was not widely taken seriously for nearly ten years. Indeed the first published interpretations of the anomaly as due to oscillations were largely from outside the experimental groups[16]. To be fair though, it seems to be the Kamioka group who first seriously believed that the anomaly was due to oscillations and not simply a detector or background problem.

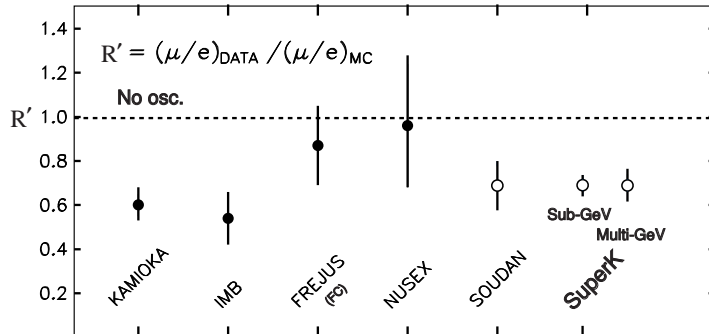
The deficit is characterized usually as an  $R$  value, the double ratio of muon to electron neutrinos, observed to expected. The effect was large, the observed  $R$  at about 2/3 of the expected value. With the initial evidence, the oscillations could have been from muon neutrinos to others (eg.  $\nu_\tau$  or a new neutrino) or between the muon and electron neutrinos themselves. It was the ratio that was in deficit: one could not be sure whether there was an excess of electron neutrinos, a deficit of muon neutrinos, or some of both. This led to suggestions of other possible “physics” causes, such as nucleon decay favoring electron modes (since the anomaly was not initially detected above the nucleon mass), or an excess of extraterrestrial electron neutrinos. See Table 1.1 for a graphical summary of the situation. There were also suggestions of systematic problems, such as problems in muon identification, something wrong with flux calculations or neutrino interaction cross sections, entering backgrounds, or generic problems with the water Cherenkov detectors.

Over the intervening years between the emergence of this “atmospheric neutrino anomaly”, as it became known, and the 1998 SuperK announcement, a great deal of effort went into study of these possible systematic causes of the anomaly. One troubling concern was that two European experiments, the NUSEX[17] and the Frejus[18] Detectors, did not observe any anomaly. Hence some people suspected a peculiarity of water as a target or with the employment of the Cherenkov radiation in vertex location. However, not only were the statistics of the European detectors relatively small, but as indicated by more recent work from a similar type of instrument in the US, the Soudan II detector[19], the presence of a surrounding veto counter is vital for the more compact type of slab detectors. As well, the MACRO experiment[22] has elucidated the non-negligible production of low energy (hundred MeV) pions by nearby cascades in rock, which particles enter cracks in non-hermetic detectors and appear to be neutrino interactions. In any case the Soudan II with now significant exposure (4.6 kiloton-years) finds an  $R$  value close to that of SuperK (and IMB and Kamioka)[19].

Figure 1.3 shows these  $R$  values for the several experiments. Note that under the assumption of no oscillations all experiments should record  $R = 1.0$ , but if oscillations are taking place, then the  $R$  should be reduced but not necessarily the same value for all experiments as it depends upon the energy range being studied. The European detectors did have higher thresholds which may partly explain their failure to detect the anomaly.

## 1.2 The Super-Kamiokande Revolution

We now proceed to summarize the evidence for oscillations which while depending largely upon the SuperK experiment, has important confirmation and consistency of results from Soudan II and MACRO (and consistency with previous smaller experiments as well, except as discussed below). Before going on it may be worthwhile to point out what permitted the big



**Fig. 1.3.** The double ratio  $R$  of muon to electron neutrino events, data divided by expectations for various underground atmospheric neutrino detectors. From A. Mann[20]

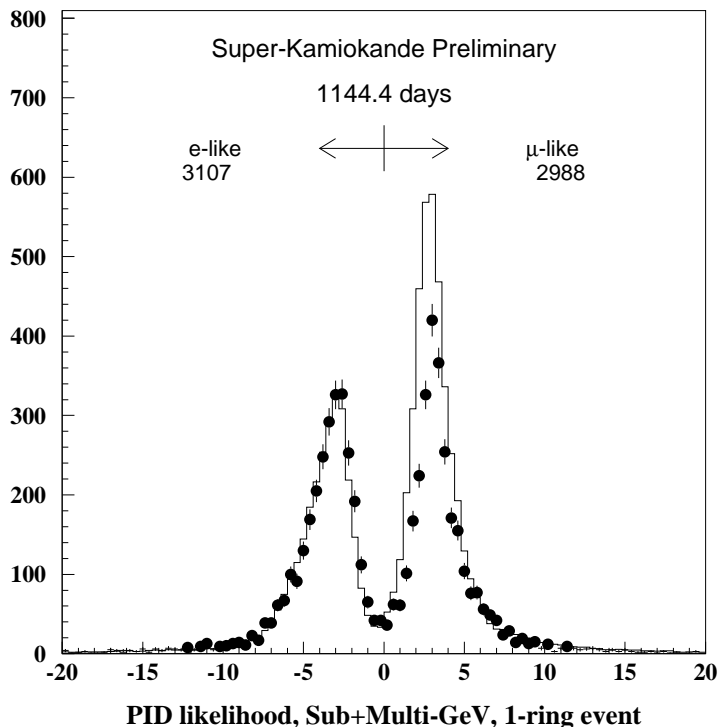
break-through with SuperK, which may not be obvious. The increase in size of detector, from near kiloton fiducial volumes for Kamioka and Soudan, and three kilotons for IMB to the twenty-two kilotons of SuperK is not the whole story. As will be seen below, the most striking progress comes from the recording of muon events with good statistics in the energy region above 1  $GeV$ . This is due to detector linear dimensions as well as gross target volume: muon events with energy more than 1  $GeV$  and thus 5  $m$  range were not likely to be fully contained in the Kamioka detector (or the IMB detector). SuperK in contrast has decent muon statistics up to almost 5  $GeV$ , and this turns out to be crucial.

The most important data to be discussed below is the “fully contained” ( $FC$ ) single-ring event sample, consisting of those events in which both the neutrino interaction vertex and resulting particle tracks remain entirely within the fiducial volume. For these events the relativistic charged particle energy and direction are well determined. We shall use the notation  $FC$  for the single ring events, which are about 2/3 of the total, arising mostly from quasi-elastic charged-current interactions in which the recoil nucleon is not seen. The multi-ring events have not yet been much used in analysis due to the ambiguous interpretation of overlapping rings from track segments in a Cherenkov detector (except as discussed below in the case of tests distinguishing the muon neutrino’s oscillating partner). Moreover, the multi-pion final states are not modeled reliably in simulations as yet, and there are further complications of final state nuclear scattering as well.

There are also “partially contained” ( $PC$ ) events, in which a muon exits the fiducial volume from a contained vertex location. Such events are useful even though the total energy is not known, the energy observed being a lower limit. Of course this is the case even with  $FC$  events, though to a lesser degree, because the observed particles are not of the same energy (or

direction) as the incident neutrino, which of course is what one would like to know.

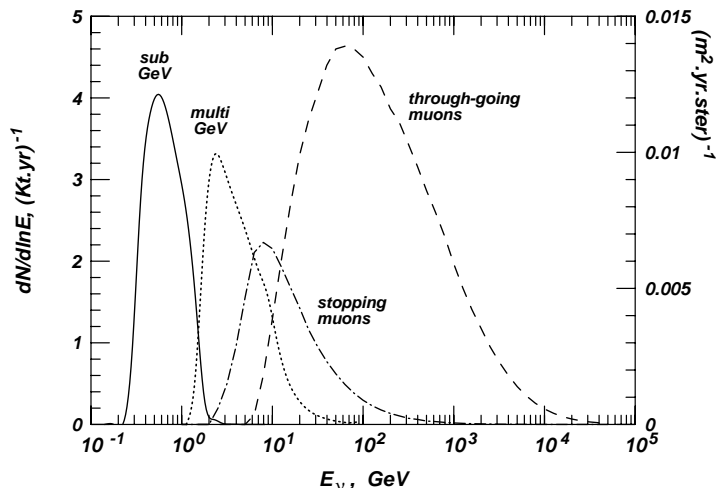
The particle types are identified by pattern recognition software, now well tested and verified by experiment with known particle beams at the accelerator[48]. Fortunately most of the contained events show single (Cherenkov radiating) tracks in which the identification is quite clean (at the 98% level), as illustrated in Figure 1.4. To be clear and cautious we usually refer to the reconstructed events as “muon-like” and “electron-like”, though a safe approximation is that these represent muon and electron neutrino charged-current interactions.



**Fig. 1.4.** Particle identification parameter distribution of the SuperK fully contained single ring data, and Monte Carlo simulation, illustrating the electron-like and muon-like separation[21].

The other two categories of events which we shall discuss are the through-going upwards-moving muons ( $UM$ ), produced by neutrino interactions in the rock or outer detector, and which are coming from directions below the horizon (as those from above the horizon can be confused with down-going muons from cosmic ray interactions in the atmosphere near overhead). Another category of event is the entering-stopping muon ( $SM$ ). It is useful that

these event categories probe approximately three different energy ranges of neutrinos:  $FC \simeq 1 \text{ GeV}$ ;  $PC$  and  $SM \simeq 10 \text{ GeV}$ ;  $UM \simeq 100 \text{ GeV}$ . This is illustrated in Figure 1.5. It should be understood that as far as we know, these neutrinos are all produced in the upper atmosphere by cosmic ray interactions, and are reasonably well described by models in content, energy, and angular dependence (to a few percent)[3].



**Fig. 1.5.** Event rates as a function of neutrino energy for fully contained events ( $E < 1.3 \text{ GeV}$  and  $E > 1.3 \text{ GeV}$ ), stopping muons (and similarly partially contained events), and through-going muons. From Engel[4].

We shall not take up limited space here with the description of the SuperK detector, which is well documented elsewhere. The interested reader would do well to look at some of the theses from SuperK, which are available on the web[25]. The short summary is that the SuperK detector consists of a large stainless steel cylinder (37 m high by 34 m diameter inside the inner detector) containing a structure holding 13,142 large (20 inch diameter) photo-multipliers. With extremely high photo-cathode coverage (40%), nearly an acre of photocathode and ten times more pixels than any earlier instrument, the instrument possesses a remarkable sensitivity of roughly eight photoelectrons per MeV of deposited (Cherenkov radiating) energy. The latter permits detection of events down to  $< 5 \text{ MeV}$ , so for the present discussion detection efficiency versus energy is not important because the events we are discussing are all above  $\simeq 100 \text{ MeV}$ . The inner volume is also well protected by a 2-m-thick, fully-enclosing veto Cherenkov counter, populated by 1800 recycled IMB (8 inch) photo-multipliers with wavelength shifting collars. The inner “fiducial” volume is further taken as 2 m inside the inner photo-multiplier surface, resulting in the 22.5 kiloton volume used for most reported data.



The SuperK oscillations claim was first formally presented to the physics community in June 1998 at the *NEUTRINO98* meeting in Takayama, Japan. The data were presented in several papers to the community[26,27,28], building upon past data from Kamioka[15] and IMB[14], and culminating in the claim of observation of oscillations of muon neutrinos, published in Physical Review Letters in August 1998[29]. We now proceed to review the evidence, which has changed little except for new indications that the  $\nu_\mu$  oscillating partner is probably the  $\nu_\tau$ , and not a hypothetical sterile neutrino.

### 1.2.1 Up-Down Asymmetry

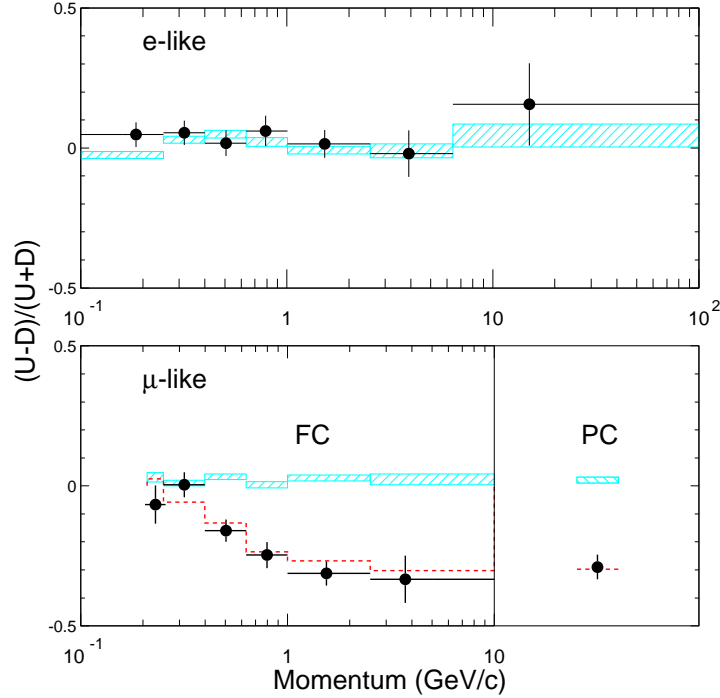
One way to look at the *FC* (and *PC*) data is in terms of a dimensionless up-to-down ratio, difference over sum (which has symmetrical errors in contrast to just up/down)[31]. Downwards going neutrinos have flown  $\sim 20 - 700$  km while up going neutrinos have traveled  $\sim 700 - 10,000$  km. The angle between the neutrino and observed charged lepton is on average of the order of  $40^\circ / \sqrt{E_\nu / \text{GeV}}$ , and the typical observed energy is a half the neutrino energy. Thus the mixing of the hemispheres of origin of the events is important only for the lowest energies (below roughly 400 MeV). This asymmetry quantity is exhibited as a function of charged particle momentum in Figure 1.6, for both electrons and muons, with the *PC* data shown as well (for which we know only a minimum momentum), from an exposure of 70.4 kiloton years in SuperK. One sees that the electron data fit satisfactorily to no asymmetry, whilst the muon data show strong momentum dependence, starting from no asymmetry and dropping to about -1/3 above 1.3 GeV.

From this Figure alone, without need for complex and often opaque Monte Carlo simulations, assuming the cause of deviation from uniformity to be due to neutrino oscillations, one can deduce that:

1. The source of the atmospheric neutrino anomaly is largely due to disappearing muons, not excess electrons.
2. There is little or no coupling of the muon neutrino to the electron neutrino in this energy/distance range.
3. The oscillations of the muon neutrinos must be nearly maximal for the asymmetry to approach one third.
4. The scale of oscillations must be of the order of 1 GeV/200 km, plus or minus a factor of several.

In fact, as seen by the dashed lines overlying the data points, the simulations do produce an excellent fit to the muon neutrino oscillation hypothesis, while the no-oscillations hypothesis is strongly rejected. The latter is so strong that statistical fluctuations as the cause of the deviation are completely improbable; one must look for systematic problems in order to escape the oscillations explanation.

One concern for some people has been the fact that the asymmetry is indeed maximal, which makes it appear that we are very lucky that the earth



**Fig. 1.6.** The up-to-down asymmetry for muon (2486) and electron (2531) single ring fully contained and partially contained (665) events in SuperK, from 1144.4 days of live time (analyzed by 6/00), as a function of observed charged particle momentum. The muon data include a point for the partially contained events (*PC*) with more than about 1 *GeV*. The hatched region indicates no-oscillation expectations, and the dashed line  $\nu_\mu - \nu_\tau$  oscillations with  $\Delta m^2 = 3.2 \times 10^{-3} \text{eV}^2$  and maximal mixing[21].

size and cosmic ray energies are “just so” to produce this dramatic effect. This appears to this author to fall in the category of lucky coincidences, such as the angular diameter of the moon and sun being the same as seen from earth. There is another oscillations related peculiar coincidence that the matter oscillation scale turns out to be close to one earth diameter, and this depends upon the Fermi constant and the electron column density of the earth. The phase space for “coincidences” is very large, and we humans are great recognizers of such patterns.

### 1.2.2 Neutrino Flux Dependence Upon Terrestrial Magnetic Field

The effect of the earth’s magnetic field on the atmospheric neutrino flux is a little complicated, but only important for very low energies. For example

for energies of a few GeV, the magnetic field provides some shielding from straight downwards going charged cosmic rays in regions near the magnetic equator. For higher energies and incoming trajectories near the horizon, the magnetic field still prevents some arrival paths. As the SuperK detector location is not on the magnetic equator the effect is not up-down symmetric, and this spoils the symmetry otherwise expected from the neutrinos about the horizontal plane. However, the effects are mostly limited to neutrino energies below about 1 GeV, corresponding to cosmic ray primaries below about 10 GeV. The picture is made a bit more complicated by the earth's magnetic field not being a nice symmetrical dipole. Fortunately there are good models of the magnetic field, and the people who have made flux calculations take these effects into account, though (in the past) largely through a simple cutoff momentum versus location. More recent calculations trace particles backwards in the magnetic field and determine trajectories that escape to infinity[23]. Lipari has, however, recently shown that the double humped cosmic ray spectra seen in the AMS experiment, with a space borne magnetic spectrometer in low earth orbit, may be due to particles in trapped orbits[24]. Moreover, Lipari points out that there are hints in the AMS data of a North-South asymmetry, which could bias the neutrino flux calculations, and even pull the derived value of  $\Delta m^2$ . However, it should be emphasized that the effect of such variation from simple expectations will only bias the lowest energy data in SuperK (roughly below 400 MeV), and analysis has demonstrated that the results quoted herein are stable against raising the acceptance energy for the data sample.

The SuperK group has published a paper[28] examining the azimuthal variation of the SuperK data ( $\pm 30$  deg about the horizon) for intermediate to higher energies (400 – 3000 MeV), in an energy region where the calculations are thought to be reliable. Indeed the SuperK data do exhibit significant variation from uniformity while fitting the flux predictions very well, giving one confidence in the modeling[28].

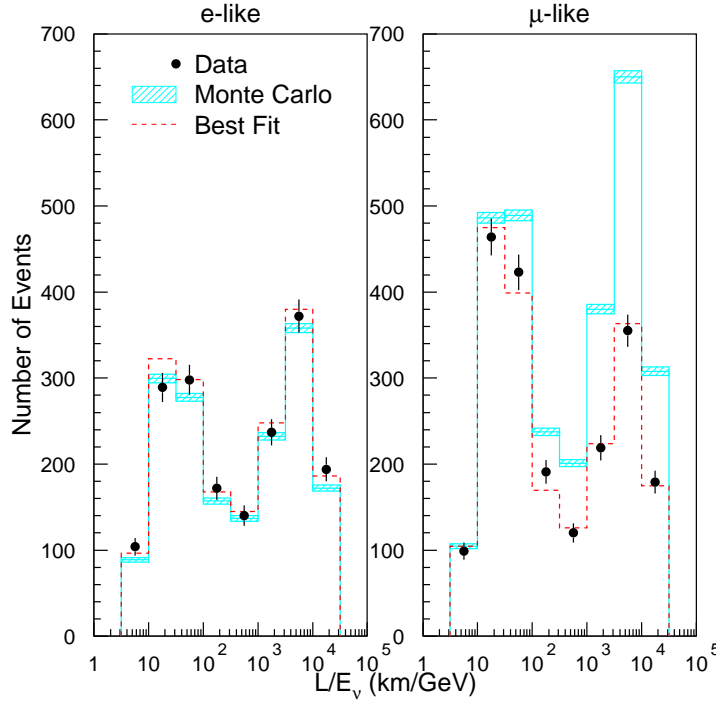
### 1.2.3 Natural Parameters for Oscillations: $L/E$

In an ideal world, one would assuredly study these data as a function of distance divided by energy,  $L/E$ , since that is the parameter in which one expects to see oscillatory behavior. For two-neutrino mixing with mass squared difference,  $\Delta m^2$ , and mixing angle  $\theta$ , the probability of a muon neutrino of energy  $E_\nu$  remaining a muon neutrino at distance  $L$  is given by[63]

$$P_{\mu\mu} = 1 - \sin^2(2\theta) \sin^2 \left( 1.27 \frac{\Delta m^2}{eV^2} \frac{L}{km} \frac{GeV}{E_\nu} \right). \quad (1.2)$$

However, since we observe only the secondary charged particle's energy and direction, badly smeared at the energies available ( $L/E_\nu$  smeared by about a factor of two), plots in which one would wish for visible oscillations can

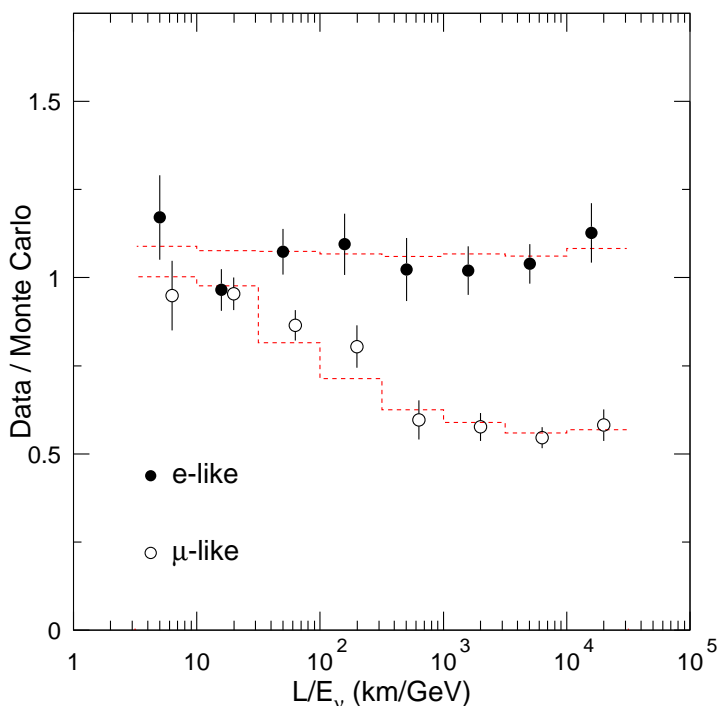
at best show a smooth slide from the no-oscillations region to the oscillating regime. This is illustrated in Figures 1.7 and 1.8, where the numbers of events, and the ratios of those numbers of events observed to those expected with no-oscillations, are plotted versus “ $L/E$ ” [32], for muon and electron (type) events. The updated data are preliminary from the SuperK 1144 day sample.



**Fig. 1.7.** The numbers of SuperK events observed compared to predicted as a function of the natural oscillations parameter,  $L/E$ , distance divided by energy. The results are not normalized. The two peaks correspond to generally down-coming (left) and up-coming (right). One sees that the muon deficit begins even in the upper hemisphere. The shaded area indicates no-oscillations expectations, and the dashed line in the fit for  $\nu_\mu - \nu_\tau$  oscillations with maximal mixing and  $\Delta m^2 = 0.0032 \text{ eV}^2$ . [21]

The plot is not “normalized”, and we see somewhat of an excess of electron type events overall (+8%). This is a little worrisome, but acceptable since (as already noted) the absolute flux is uncertain to a larger value. In contrast to the electron data, the muon points fall relative to no-oscillations expectations with increasing  $L/E$  beyond about  $50 \text{ km/GeV}$ , reaching a plateau at about one half their initial value, consistent with maximal mixing. Muon (to tau) neutrino oscillations in the Monte Carlo simulation are indicated by a dotted lines, and fit the data reasonably well.

As noted, these data do not (and could not) show oscillations, due to convolutions washing out the oscillatory behavior. It was this smooth fall, however, that caused the author and some colleagues to wonder if another model might fit the data, one in which one component of the muon neutrino decays rather than oscillates with distance. Two papers[33,34] suggested neutrino decay to explain the atmospheric neutrino anomaly. I will not discuss details here, but note that in order to construct a viable model we had to push on all available limits, and invoke neutrino mass and mixing in any case. Consequently such models do not pass the economy test of Occam's Razor, though most annoyingly they remain not ruled out as yet.



**Fig. 1.8.** The ratio of numbers of events observed compared to predicted as a function of the natural oscillations parameter, distance divided by energy. The results are not normalized and overall there is a slight excess (about 8% compared to a systematic uncertainty of 25%) compared to expectations. Electrons show no evidence for oscillations, while muons exhibit a strong drop with  $L/E$ . This is consistent with  $\nu_\mu - \nu_\tau$  oscillations with maximal mixing and  $\Delta m^2 = 0.0032 \text{ eV}^2$ , as indicated by the dashed lines from the simulation.[21]

One may note that detecting multiple oscillation peaks is not ruled out in principle for detectors such as SuperK or Soudan II, employing the atmospheric neutrinos. It is a matter of recording the final state of the muon

neutrino charged current events, including nuclear recoil, with sufficient accuracy and statistics. Detectors such as a liquid argon device of the ICARUS type are claimed to have the resolution, if large enough. Soudan II has apparently good enough resolution to accumulate a “golden sample” in which the nuclear recoil is detected, permitting reconstruction of incident neutrino energy and direction. Unfortunately Soudan II does not have enough mass to achieve definitive statistics in a practical observing period[19]. Another possibility is that SuperK with enough exposure and more highly developed analysis would be able to accumulate an adequate sample of events in which the recoil proton is detected above Cherenkov threshold. At the moment none of the above promise success.

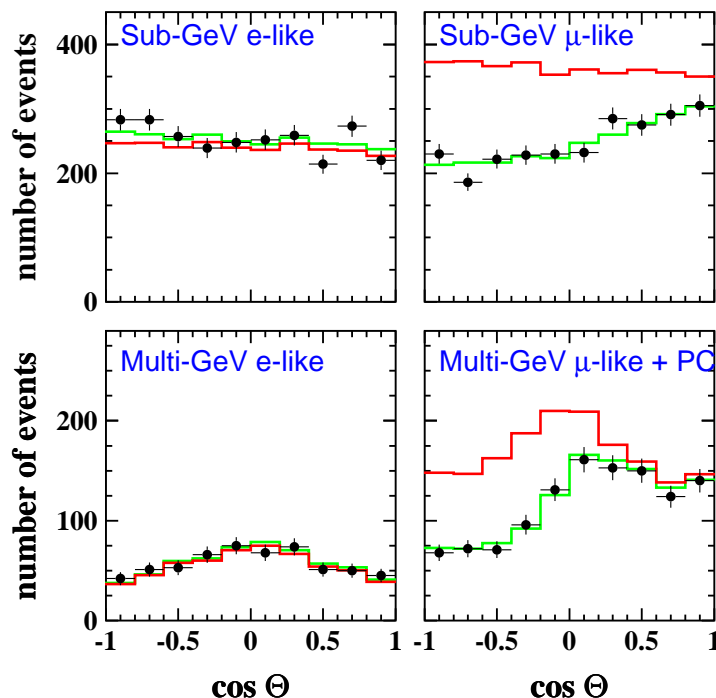
Considering future experiments, the attempt to discern oscillations as a function of  $L/E$  is one area in which improvement may indeed be made. The MINOS[60] detector in Minnesota with a neutrino beam from Fermilab, and the large detectors to be constructed in Gran Sasso, ICANOE[61] and OPERA[62], detecting a neutrino beam from CERN, give some hope of being able to yield oscillatory plots. A hypothetical detector, such as a megaton version of the Aqua-RICH instrument studied by Ypsilantis and colleagues could have the resolution to see a multi-peaked  $L/E$  plot[35,36]. Nearer to technical development, the proposed MONOLITH experiment would consist of a 30 kiloton pile of magnetized iron and tracking detector layers, and employ the cosmic rays to detect the first dip in  $L/E$  in the upcoming muon flux through the earth[37].

#### 1.2.4 Energy and Angle Variation

The SuperK Collaboration’s preferred method of fitting the ensemble (single ring)  $FC$  and  $PC$  data is to employ a  $\chi^2$  test to numbers of events binned by particle type, angle, and energy, a total of 70 bins. The bin choices may seem a bit peculiar, but they have historical precedent (they are as employed for Kamiokande) and though not optimal for the new data set, this choice permits avoidance of any statistical (or confidence) penalty for choosing arbitrary bins. The fit employs a set of parameters to account for potential systematic biases. Details cannot be presented here, but it has been shown that the numerical results are quite insensitive to the selection of the parameters or their supposed “errors” (except for the overall normalization)[38]. This method of systematic error handling has been shown to be equivalent to employment of the correlation matrix of parameters[32].

Figure 1.9 illustrates the data plotted for two energy intervals ( $sub-GeV$  and  $multi-GeV$ , less or more than  $1.3 GeV$ ) for single track events identified as either electron-like or muon-like. The partially contained data is displayed with the multi-GeV muon data. The data are shown as a function of the cosine of the zenith angle, with +1 being down-going. One sees that the data very well fit the curves from the Monte Carlo simulation, at the values gotten

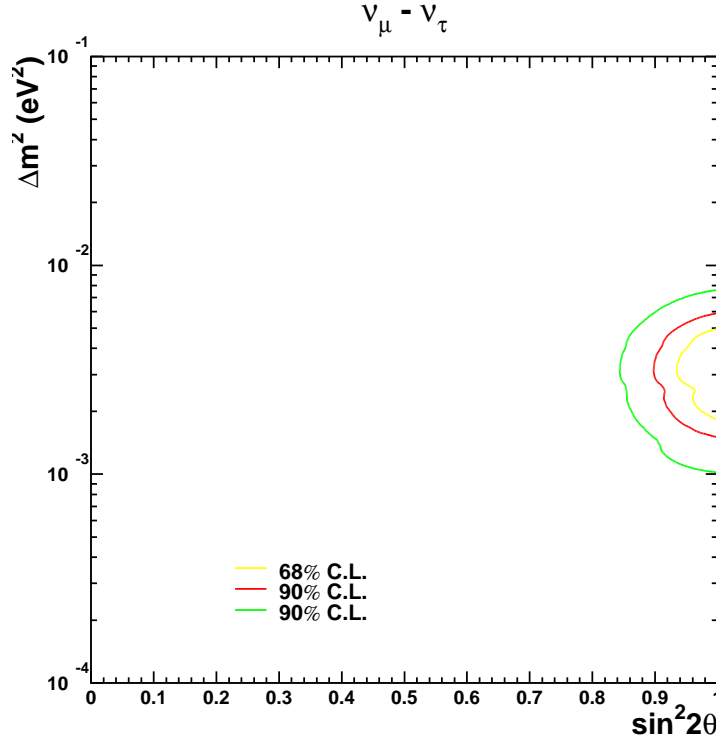
from the grand ensemble fit,  $\Delta m^2 = 0.003 \text{ eV}^2$  and  $\sin^2(2\theta) = 1.0$ . The limit on  $\Delta m^2$  is 0.002 to 0.007  $\text{eV}^2$ , and  $\sin^2(2\theta) > 0.85$  at 90% confidence level.



**Fig. 1.9.** Cosine of zenith angle distributions of the contained and partially contained event data for two different energy ranges (above and below 1.3  $\text{GeV}$ ), electron and muon single ring events. 1144 live days of SuperK data (preliminary analysis) are indicated by dots with statistical error bars. The solid line shows no-oscillations simulation result, and the hatched line that for oscillations between muon and tau neutrinos with best fit  $\Delta m^2 = 0.0032 \text{ eV}^2$  and maximal mixing[21].

The results of the fits are often presented in terms of an inclusion plot, showing an acceptable region(s) in the space of mixing angle ( $\sin^2 2\theta$ ) and mass squared difference ( $\Delta m^2$ ), as presented in Figure 1.10. The  $\Delta m^2$  value at  $\chi^2$  minimum has moved a little upwards with accumulated statistics, though not much, (good news for long baseline experiments anyway) but remains uncertain to about a factor of two.

It is noteworthy that the earlier indications of and constraints upon oscillations parameters from Kamiokande, IMB and Soudan gave somewhat larger values of  $\Delta m^2$ . All of these results depended upon fitting the  $R$  value, since no angular distribution was discerned (due to limited statistics and lower mean energy due to containment). Later Kamiokande data did show angular variation in the PC data, but not statistically compellingly. For some reason



**Fig. 1.10.** Inclusion plot, showing the regions for 3 levels of statistical acceptability in the plane of mixing angle and mass squared difference for  $\nu_\mu - \nu_\tau$  oscillations. This is from SuperK contained and partially contained event 1144 day data preliminary analysis of June 2000[21].

not fully understood, the fits using  $R$  alone all seem to yield higher values of  $\Delta m^2$ . If one has some deficit in muons without angular determination, then one can fit that suppression with any  $\Delta m^2$  above some threshold value by choosing an appropriate mixing angle. Thus the  $R$  constraints are open ended upwards in  $\Delta m^2$ . Perhaps there is a systematic problem here due to predicted neutrino spectra, or perhaps there is some physics yet to be elucidated. This is not to suggest that it seems possible for the preferred two-neutrino solution to move much, but that more complex small effects at the  $< 10\%$  level could be superposed on the present simple solution. Accelerator based experiments should clarify this issue.

### 1.2.5 Muon Decay Events

It is not often emphasized, but the original indication of the anomaly, a deficit in stopped-muon decays ( $\simeq 2.2 \mu\text{sec}$  after the initial neutrino event), remains with us, and constitutes a nice alternate sample, almost independent



and with quite different systematics. It is not so clean a sample (there are muon decays from pions produced in electron CC and all flavor NC events) and the statistics are lower, but the complete consistency of the muon decay fraction remains a reassuring complement to the energy and angle analysis employing track identification.

### 1.2.6 Through-Going and Entering-Stopping Muons

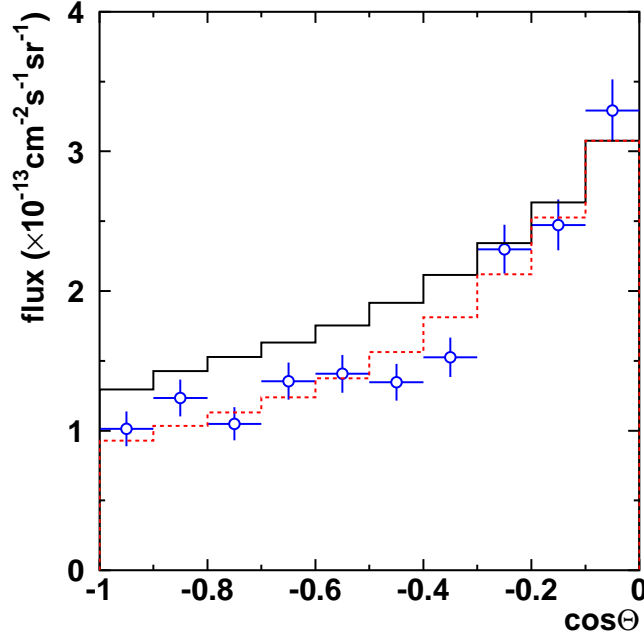
Another cross check comes from the *UM* and *SM* samples, which are particularly attractive because the source energies are factors of 10 and 100 higher and the detector systematics rather different (for example, the target is mostly rock not water). A drawback to these samples is that one is restricted to using muons arriving from below the horizon, due to the overwhelming number of down-going cosmic ray muons penetrating the mountain (at 50,000 times the rate in SuperK).

In going from the earlier instruments to SuperK, however, the gain is not so great (the 1200  $m^2$  of SuperK being about a factor of three more than the previously largest underground instrument, IMB, for example), since the rate of collection of through-going muons depends upon area not volume. However, the much greater thickness of the detector (and the efficient tagging of entering and exiting events in the veto layer) yields many more entering-stopping (*SM*) events.

The flux angular distribution derived from 1260 *UM* events from below the horizon, each with more than 7  $m$  track length in the detector, is shown in Figure 1.11, where one sees that the angular distribution is nicely consistent with oscillations and not with no-oscillations. However, since much of the effect is close to the horizon, where oscillations for the energies in question are just setting in, one worries about contamination of the near horizon events with in-scattered events from the much greater numbers of down going muons. There is no room for detail here, but SuperK does perform a small background subtraction (9 events of 247, or 3.6% in that one bin) for events within 3 degrees of the horizon, but otherwise finds no evidence for significant contamination[30].

In SuperK the *SM* sample was predicted to be 33-42% of the *UM* sample, as indicated in Figure 1.12, yet in fact SuperK sees only about  $24\% \pm 2\%$ . Fitting the data to the oscillation hypothesis, one can make the now usual inclusion plot, which shows that the *UM* and *SM* results are completely in accord with those from the *FC* and *PC* data, see Figure 1.23. However, as the statistics are smaller and the physics leverage not as great, the muon result does not add much to the *FC* and *PC* constraints, though it does stiffen the lower bound in  $\Delta m^2$ . The joint fit to the *UM* and *SM* data alone yields a  $\chi^2/ndf = 35.4/15$  and  $13/13$  for the cases of no-oscillations and  $\nu_\mu - \nu_\tau$  oscillations.

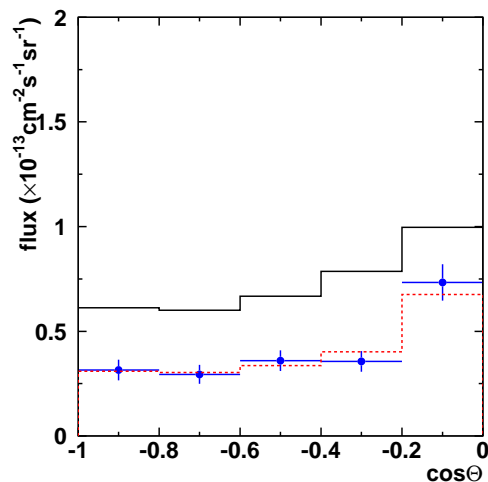
One may note that earlier experiments, such as IMB, with a final sample of 647 events, no veto counter and less mature flux calculations, did not



**Fig. 1.11.** The preliminary flux calculated from 1260 upcoming muons during 1138 live days of SuperK data, with 9 events background subtracted in bin nearest the horizon,  $\cos(\Theta) = 0$ . Error bars show statistical errors only. Expectations for no-oscillations (solid line) and the best fit for  $\nu_\mu - \nu_\tau$  oscillations with  $\Delta m^2 = 0.0032 \text{ eV}^2$  and maximal mixing (dashed line), are shown[21].

find any net deficit in the UM sample, nor significant deviation from no-oscillations expectations. A similar case obtained with other smaller data sets. Indeed, one may note that on the strength of the SuperK UM data angular distribution alone, one would hardly be making discovery claims. All UM data from IMB and Kamioka are and were in accord with the present results, but not demanding of the oscillations conclusion.

There is a lengthy tale about an  $SM/UM$  analysis from the IMB experiment[14], which claimed an exclusion region very close to the now preferred solution. The IMB stopping muon sample was small and it was not clean due to lack of a veto layer. More importantly the interpretation seems to have been flawed due to older flux models and Monte Carlo simulations. Work is in progress to reassess the old data with new flux calculations and an updated quark model[39]. Thus there remains a cloud upon the horizon, but one which may fade away upon reanalysis. It might also be worth recalling that in the 1980's the absolute rate of upcoming muons as measured in the IMB, Kamioka and other detectors, agreed with calculated rates employing then available flux



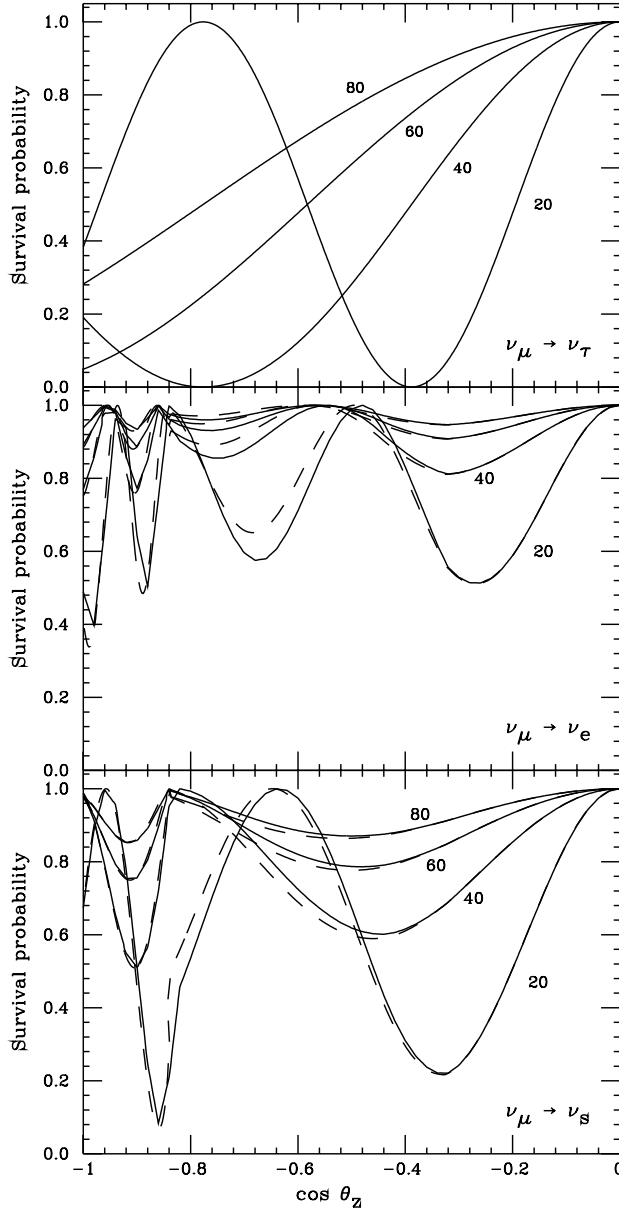
**Fig. 1.12.** The flux of stopping muons versus zenith angle in 1117 days of SuperK data. There are 311 events and a background of 21.4, with track length greater than 7 m, or about 1.6 GeV. The large overall deficit in the data (dots with statistical error bars) compared to the no-oscillations (solid line), is less significant than it appears because of the 20% uncertainty in absolute flux[21].

calculations. Also at that time, peculiar angular distributions which fit no expectation were reported at conferences from the MACRO and Baksan detectors. These results all tended to give pause to claiming oscillations as the resolution of the atmospheric neutrino anomaly. These concerns were swept away by the clean and statistically convincing *FC* muon angular distributions from SuperK.

### 1.2.7 The Muon Neutrino’s Oscillation Partner

Given that the muon neutrino is oscillating, is it oscillating with a tau neutrino or a new sterile neutrino which does not participate in either the charged (CC) or neutral current (NC) weak interaction? Fortunately there exist several means to explore this with SuperK data. The NC interactions should show an up-down asymmetry for sterile neutrinos but not for tau neutrinos (since the NC interactions for all ordinary neutrinos are the same). Another avenue for discrimination is that sterile neutrinos would have an additional oscillation effect due to “matter effects”. The consequence would be a unique signature in the angular distribution of intermediate energy muons, as illustrated in Figure 1.13.

Early SuperK efforts focused upon the attempt to collect a clean sample of  $\pi^0$  events. As it turns out, this was frustrated because the rings (from the two

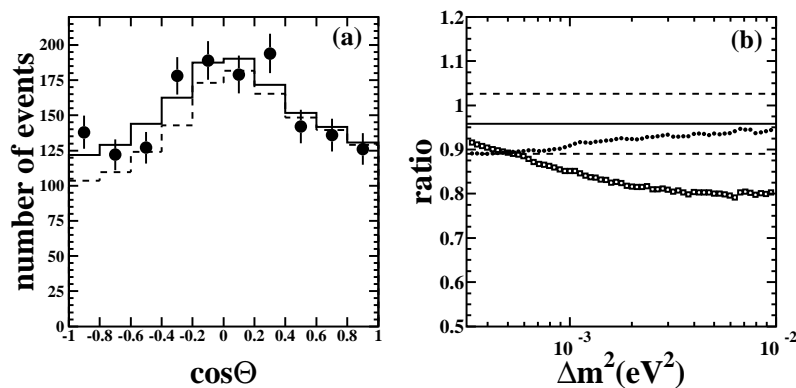


**Fig. 1.13.** Survival probability  $P(\nu_\mu \rightarrow \nu_\mu)$  as a function of the zenith angle in the cases of maximal mixing of  $\nu_\mu$  with  $\nu_\tau$  (upper panel),  $\nu_e$  (middle panel) and  $\nu_s$  (lower panel). For  $|\Delta m^2| = 5 \cdot 10^{-3} \text{ eV}^2$  the curves correspond to neutrino energies 20, 40, 60 and 80 GeV. The dashed curves are calculated with the approximation of constant average densities in the mantle and in the core of the earth. From Lipari[40].

decay  $\gamma$ s) cannot be separated at energies above  $\simeq 1 \text{ GeV}$ , and in net there are not so many reconstructed events as to permit a good discrimination. In fact the absolute rate is consistent with expectations, but the cross section is uncertain to about 20% making the hint at tau coupling not significant. The  $K2K$  experiment should soon measure this cross section to perhaps 5% however, making the  $\pi^0$  rate a useful discriminant.

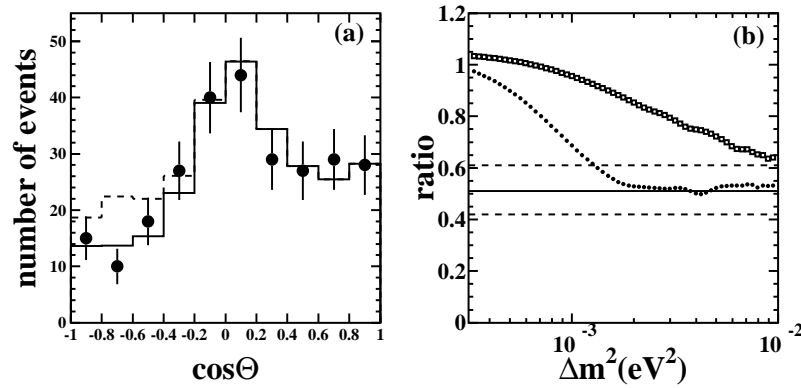
More recently, tests have been devised employing a multi-ring sample ( $MR$ ), the  $PC$  event sample, and the  $UM$  sample, all of which are independent of the single ring  $FC$  sample which yields the strongest oscillation parameter bounds.

The  $MR$  sample is cut by energy ( $> 1.5 \text{ GeV}$ ) and the requirement of the dominant ring being electron-like to enhance the NC content of the sample. A test parameter is constructed from the ratio of events from within sixty degrees of the zenith and nadir. This is illustrated in Figure 1.14, where one sees consistency of  $\nu_\tau$  and disfavoring of  $\nu_{sterile}$ .



**Fig. 1.14.** (a) Zenith angle distributions of the multi-ring events satisfying cuts as described in the text.  $\cos\Theta$  is +1 for down-going events. The black dots indicate the data and statistical errors. The solid line indicates the prediction for tau neutrinos, and the dashed for sterile neutrinos with  $(\Delta m^2, \sin^2 2\theta) = (3.3 \times 10^{-3} \text{ eV}^2, 1.0)$ . These two predictions are normalized by a common factor so that the number of the observed events and the predicted number of events for  $\nu_\mu \leftrightarrow \nu_\tau$  are identical. (b) Expected up/down ratio as a function of  $\Delta m^2$ . Horizontal lines indicate data (solid) with statistical errors (dashed). Black dots indicate the prediction for tau neutrinos, and the empty squares for sterile neutrinos, both for the case of maximal mixing[41].

The  $PC$  sample can be cut on energy (requiring  $> 4 \text{ GeV}$ ) in order to achieve a higher neutrino source energy, and the upwards going number compared to downwards number of events. In this instance one is seeking matter effects, and the results are shown in Figure 1.15, indicating again a preference for  $\nu_\tau$  over  $\nu_{sterile}$ .

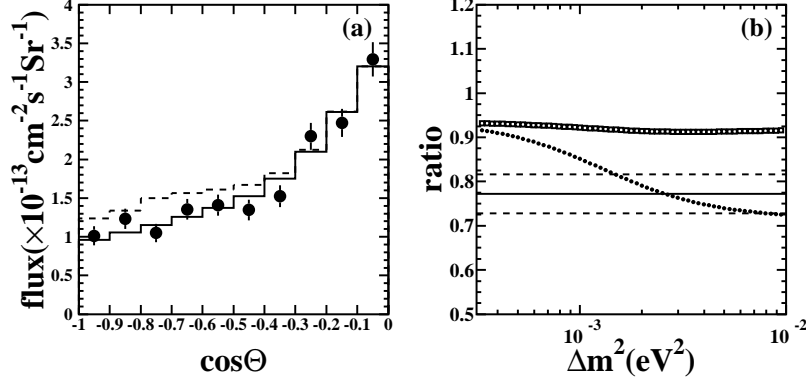


**Fig. 1.15.** (a) Zenith angle distributions of partially contained events satisfying cuts of  $E_{vis} > 5 \text{ GeV}$ .  $\cos \Theta$  is +1 for down-going events. The black dots indicate the data and statistical errors. The solid line indicates the prediction for tau neutrinos, and the dashed for sterile neutrinos with  $(\Delta m^2, \sin^2 2\theta) = (3.3 \times 10^{-3} \text{ eV}^2, 1.0)$  (b) Expected up/down ratio as a function of  $\Delta m^2$ . Horizontal lines indicate data (solid) with statistical errors (dashed). Black dots indicates the prediction for tau neutrinos, and the empty squares for sterile neutrinos, both for the case of maximal mixing[41].

For the muons, a near horizontal number can be compared to a number of nearly straight upcoming events for another test of matter oscillations. This is presented in Figure 1.16.

Finally the three tests are combined in a single  $\chi^2$  test for the case of  $\nu_\mu \leftrightarrow \nu_\tau$  and the two cases for  $\nu_{sterile}$  heavier or lighter than  $\nu_\mu$ . This is presented in Figure 1.17, where one sees that the entire region in mixing parameter space is eliminated for sterile neutrinos at more than the 99% confidence level, whilst the  $\nu_\tau$  case fits perfectly[41]

As to muon neutrinos coupling to electron neutrinos, SuperK can say only that the  $\Delta m^2$  is out of range on the low side or that the sine of the mixing angle is less than about 0.1, if  $\Delta m^2$  is large. As indicated in the earlier plots with up-down asymmetry, there is surely not much mixing in this energy range. One clever scenario[45] has the electron neutrino oscillation loss



**Fig. 1.16.** (a) Zenith angle distributions of the upward moving through-going muons.  $\cos\Theta$  is -1 for vertical up-going events. The black dots indicate the data and statistical errors. The solid line indicates the prediction for tau neutrinos, and the dashed for sterile neutrinos with  $(\Delta m^2, \sin^2 2\theta) = (3.3 \times 10^{-3} \text{eV}^2, 1)$  (b) Expected up/down ratio as a function of  $\Delta m^2$ . Horizontal lines indicates data (solid) with statistical errors (dashed). Black dots indicates the prediction for tau neutrinos, and the empty squares for sterile neutrinos, both for the case of maximal mixing[41].

being just compensated by muon neutrinos splitting their oscillations between electrons and taus. This seems to be ruled out by higher energy SuperK data however[32]. Further discussions of (many) other scenarios of oscillations can be found in the Chapter IX.

### 1.2.8 Sub-Dominant Oscillations

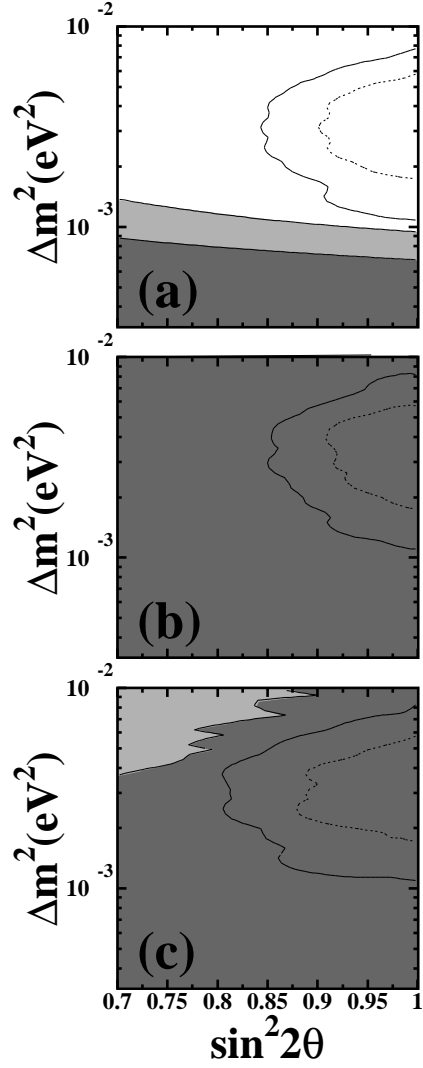
For all of the foregoing we have considered only two flavor oscillations. A simple three flavor analysis can be made employing the assumption that solar neutrino oscillations are driven by a much smaller mass difference than found for  $\nu_\mu - \nu_\tau$ ,  $m_1 < m_2 \ll m_3$ . Then, using the standard notation for three neutrino MNS mixing matrix (see Chapter IX), the oscillation probabilities can be written as:

$$P_{\nu_\mu \nu_\mu} = 1 - 4 \sin^2(2\theta_{23}) \cos^2(\theta_{13}) (1 - \sin^2(\theta_{23}) \cos^2(\theta_{13})) \sin^2(1.27 \Delta m^2 L/E), \quad (1.3)$$

$$P_{\nu_\mu \nu_\tau} = \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2(1.27 \Delta m^2 L/E), \quad (1.4)$$

$$P_{\nu_\mu \nu_e} = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(1.27 \Delta m^2 L/E), \quad (1.5)$$

$$P_{\nu_e \nu_\tau} = \sin^2(2\theta_{13}) \cos^2(\theta_{23}) \sin^2(1.27 \Delta m^2 L/E), \quad (1.6)$$



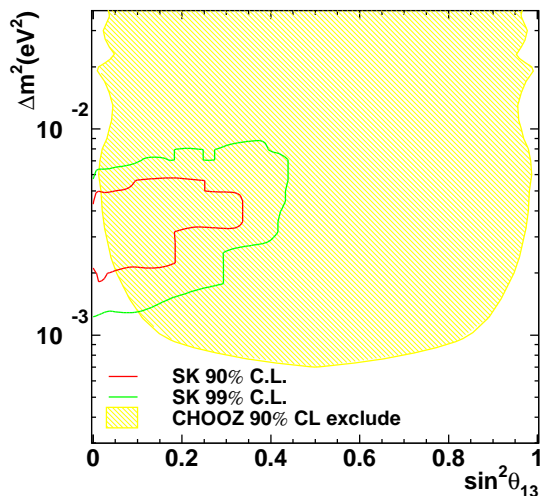
**Fig. 1.17.** Excluded regions for three alternative oscillation modes. (a)  $\nu_\mu \leftrightarrow \nu_\tau$ , the light (dark) shaded region is excluded at 90(99)% C.L., (b)  $\nu_\mu \leftrightarrow \nu_{sterile}$  with  $\Delta m^2 > 0$ , the whole region shown in this figure is excluded at the 99% C.L., and (c)  $\Delta m^2 < 0$ , whole region is excluded at 90% C.L., the dark shaded region is excluded at more than the 99% C.L.. The thin dotted (solid) line indicates the 90 (99)% C.L. allowed regions from the FC single-ring events[41].



$$P_{\nu_e \nu_e} = 1 - \sin^2(2\theta_{13}) \sin^2(1.27 \Delta m^2 L/E), \quad (1.7)$$

where  $\Delta m^2 = m_3^2 - m_2^2$ , and we neglect any consideration of  $CP$  or  $CPT$  violation.

The SuperK FC and PC data 990 day data has been fitted with these equations[46], and the limits on  $\sin^2(2\theta_{13})$  are less than 0.25 at 90% C.L., with  $\Delta m^2 = 0.003 \text{ eV}^2$ . The best fit value lies at  $\sin^2(\theta_{13}) = 0.03$ ,  $\sin^2(\theta_{23}) = 0.63$ . At this  $\Delta m^2$  the CHOOZ results allow either  $\sin^2(\theta_{13}) < 0.03$  or  $> 0.97$ , so the latter is eliminated by the SuperK results, as illustrated in Figure 1.18.



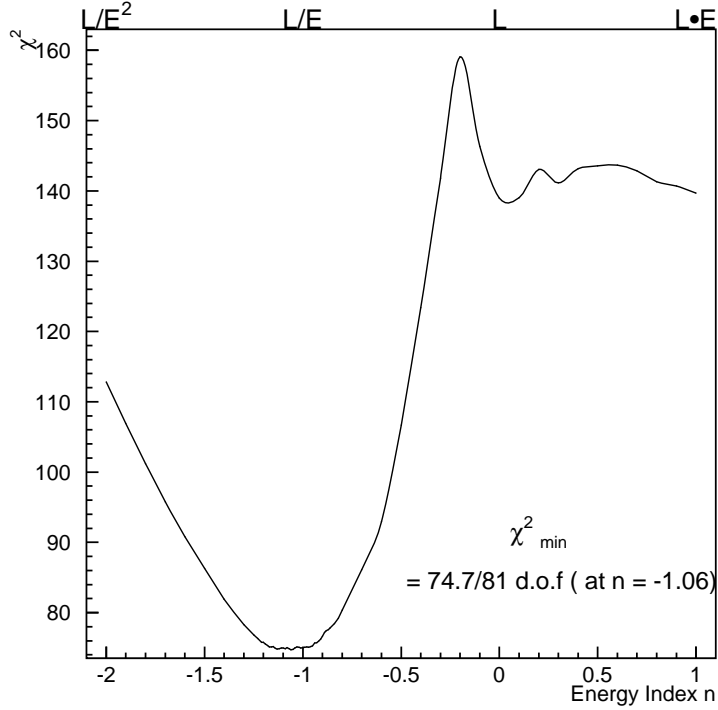
**Fig.1.18.** Three neutrino fits to the SuperK data showing 90% and 99% allowed regions. The shaded region is the 90% exclusion region from the CHOOZ experiment[46]. See text for qualifications.

### 1.2.9 Non-Standard Oscillations

As discussed in Chapter IX and elsewhere[47], there are models of neutrino oscillations which result from gravitational splitting, violations of Lorentz invariance, and so on, which result in oscillation with a phase proportional to, say,  $L \times E$  instead of  $L/E$ , or even with no energy dependence. The SuperK group has presented a fit to the data as a function of

$$P_{\nu_\mu \nu_\tau} = \sin^2(2\theta) \sin^2(\beta L E^n) \quad (1.8)$$

where  $n$ ,  $\beta$  and  $\sin^2(2\theta)$  (0.7 to 1.3) are varied. As indicated in Figure 1.19, the exotic solutions are strongly disfavored, while the normal function is perfectly acceptable, with  $n = -1.06 \pm 0.14$ .



**Fig. 1.19.** The variation of  $\chi^2$  with index  $n$  in oscillating phase for muon neutrinos, as in  $\text{const} * L * E^n$ .  $n = -1$  corresponds to ordinary oscillations. One sees that non-standard solutions with  $n$  of 0 and 1 are strongly disfavored[21].

### 1.2.10 Hypotheses to Explain Anomaly

We conclude with a summary, presented in Table 1.1, of all hypotheses put forth to explain the atmospheric neutrino anomaly. Space does not permit a full discussion here, but it is the case that the SuperK data now have eliminated almost all alternate hypotheses to explain the results.

The atmospheric neutrino flux calculations cannot be producing the anomaly since we see the effect otherwise unexplained in the muon zenith angle distribution. The cross sections cannot produce such a geographical effect, even if one could find some lepton universality breaking phenomenon. Particle identification has been heavily studied and verified at the accelerator with a 1000-ton Cherenkov detector tank[48]. Entering backgrounds, which would produce effects clustering near the outer walls, show no evidence for contribution to the anomaly in the SuperK data. Detector asymmetrical response is ruled out by the observed symmetry of the electron data, as well as detailed calibration studies with isotropic sources.

Extra-terrestrial neutrinos cannot be the culprits (unfortunately), since we see that it is a deficit of muon neutrinos causing the anomaly, not an excess

of electron neutrinos. Proton decay is ruled out similarly due to geographical dependence of the deficit, and the extent of the anomaly to too high an energy (ruling out neutron-anti-neutron oscillations as the source as well). The decay of a muon neutrino component has been discussed, and while seemingly unlikely is not totally ruled out as yet. Anomalous absorption of muon neutrinos by the earth, correlated with an exponential in the column density through the earth, is ruled out as well. This follows because the anomaly is not dominated by that small part of the solid angle going through the earth's core, whereas we see the muon deficit starting even above the horizon. Electron neutrino mixing is ruled out as the dominant effect, again due to the muon angular distribution. Sterile neutrinos do not fit the data as discussed above. As discussed in the previous section, non-standard oscillations are also ruled out.

The only hypothesis which survives, and which fits all the evidence, is that muon neutrinos maximally mix with tau neutrinos with a  $\Delta m^2$  in the range of  $2 - 7 \times 10^{-3} \text{ eV}^2$ . It is noteworthy to this author that in all the tests made on the data sample, there appears to be great stability in the results against variations of all the parameters explored.

### 1.2.11 Results from Soudan II

The Soudan 2 detector located in an old iron mine in Minnesota, USA, consists of a vertical slab, fine-grained tracking calorimeter of 963 tons total mass. The cavern has a surrounding layer of proportional tubes, 2 or 3 layers thick on all sides. Data have been reported from 4.6 kiloton years exposure[20], as illustrated in Figure 1.20. The contained events plotted are selected for lepton energy  $> 700 \text{ MeV}$  with no visible nuclear recoil, or visible energy  $> 700 \text{ MeV}$  and summed momentum  $> 450 \text{ MeV}/c$  and lepton momentum  $> 250 \text{ MeV}/c$ . The energy resolution is of order 20%, and the angular resolution of order 20-30 degrees. In the figure the predicted number of events has been normalized to the electron total. One can see that with only of the order of 100 events of each type, the statistical significance is not great, but the depletion of upcoming muon events is evident. The fits to oscillations parameters are included below, in Figure 1.23.

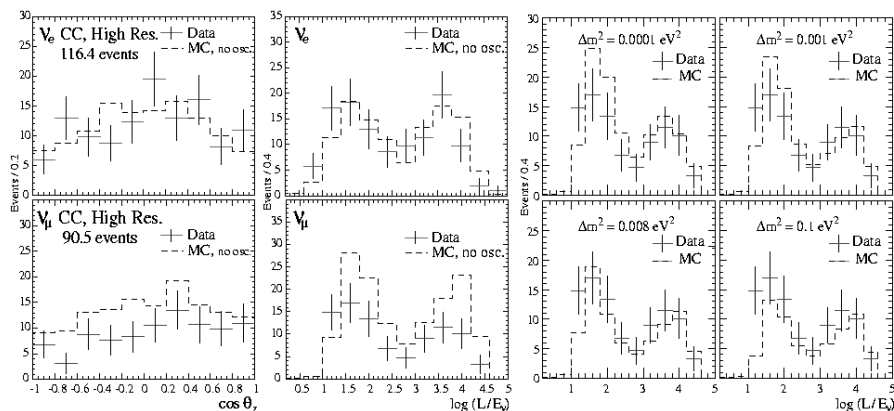
### 1.2.12 Results from MACRO

The MACRO detector, built primarily to seek monopoles, possesses a significant capability, with effective mass of 5.3 kilotons, to detect through-going and stopping muons as well as contained and partially contained neutrino interactions[42]. The instrument, located in the deep underground Gran Sasso National Laboratory in Italy, consists of horizontal planes of a tracking instrument.

Figure 1.21 shows the results of analysis of partially contained data, for which up and down cannot be distinguished, but which shows a clear deficit

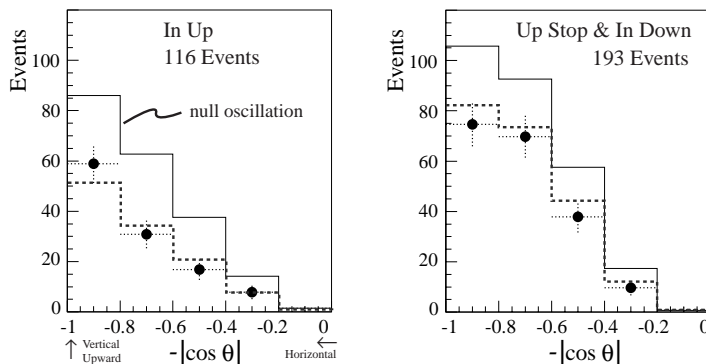
**Table 1.1.** List of hypotheses invoked to possibly explain the atmospheric neutrino anomaly. The first 3 columns are criteria available prior to SuperK, and the last 4 after the 1998 SuperK publication. The hypotheses divide into 5 systematics issues and 8 potential physics explanations. As indicated in the text, the only remaining likely hypothesis is the oscillation between muon and tau neutrinos. The “ $\times$ ” schematically indicates which evidence rules out the hypothesis in that row.

<i>Evidence</i>		<i>Old</i>				<i>New</i>	
Hypothesis	$R < 1$ $(E < 1$ GeV)	$\mu$ decay <i>Frac</i>	<i>Vol</i> <i>Frac</i>	$R < 1$ $(E > 1$ GeV)	$A_e \simeq 0$	$A_\mu < 0$	$R(L/E) \simeq 0.5$
Atm. Flux Calc.	×	✓	✓	×	✓	×	×
Cross Sections	×	✓	✓	×	✓	×	✓
Particle Ident.	✓	×	×	✓	✓	×	✓
Entering Bkgd.	✓	✓	×	✓	✓	×	✓
Detector Asym.	✓	✓	×	✓	×	✓	✓
X-Ter. $\nu_e$	✓	✓	✓	✓	✓	×	×
Proton Decay	✓	✓	✓	×	✓	×	×
$\nu_\mu$ Decay	✓	✓	✓	✓	✓	✓	✓
$\nu_\mu$ Abs.	✓	✓	✓	✓	✓	✓	×
$\nu_\mu - \nu_e$	✓	✓	✓	✓	×	✓	✓
$\nu_\mu - \nu_s$	✓	✓	✓	✓	✓	×	✓
Non-Stand. Osc.	✓	✓	✓	✓	✓	✓	×
$\nu_\mu - \nu_\tau$	✓	✓	✓	✓	✓	✓	✓



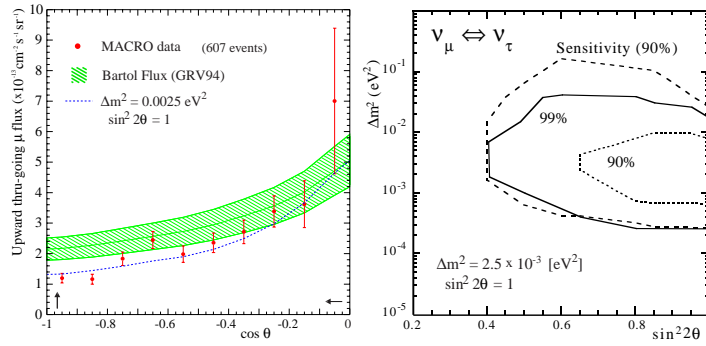
**Fig. 1.20.** (left): Distributions in  $\cos \theta_z$  for the  $\nu_e$  and  $\nu_\mu$  flavor event samples. Data (crosses) are compared to the null oscillation MC (dashed histogram) where the MC has been rate normalized to  $\nu_e$  data. (middle): Distributions of  $\log(L/E_\nu)$  for  $\nu_e$  and  $\nu_\mu$  charged current events compared to the neutrino MC with no oscillations; the MC has been rate-normalized to the  $\nu_e$  data. (right): Comparison of  $L/E_\nu$  distribution for  $\nu_\mu$  data (crosses) and expectations from neutrino oscillations for four  $\Delta m^2$  values, with  $\sin^2(2\theta) = 1.0$ . From Mann[20]

compared to expectations with no-oscillations. The acceptance of such a planar instrument is small near the horizon so most of the effect is from the nearly vertical events. The In-Up sample has 116 events and exhibits a depletion of  $0.57 \pm 0.16$  compared to expectations.



**Fig. 1.21.** Distributions in  $\cos \theta$  for MACRO partially contained events. The data (solid circles) are seen to fall below the null oscillation expectation in every bin of both samples. The dashed line shows expectations for maximal mixing and  $\Delta m^2 = 0.0025 \text{ eV}^2$ . From Surdo[42].

The MACRO detector also has a significant sample of upwards through-going muons, as illustrated in Figure 1.22. Note that the muon energy threshold is low, in the hundred MeV range (varying with angle and entry location). The overall depletion (data/expectations) is  $0.74 \pm 0.03 \pm 0.04 \pm 0.12$ , where the last term reflects uncertainty in flux and cross section[42]. While the fit to oscillations appears not to be perfect and the minimum in  $\chi^2$  lies in the unphysical region, the confidence level boundaries shown on the right in Figure 1.22 indicate consistency with the SuperK results.

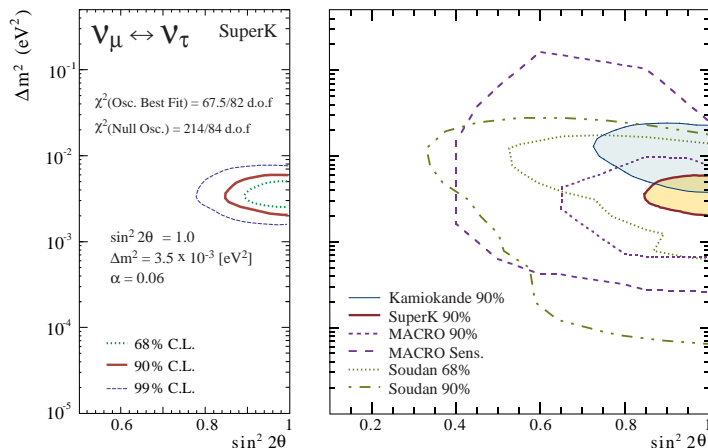


**Fig. 1.22.** a) (left): The angular distribution of upward through-going muons observed in MACRO. The data distribution (solid circles) differs from the null oscillation expectation (shaded band) in shape and in rate. b) (right): The neutrino oscillation allowed regions obtained by MACRO from the upward through-going muons. Confidence level and experimental sensitivity boundaries are calculated using the Feldman-Cousins method. From [42].

### 1.2.13 Combined Evidence

In Figure 1.23 on the left is the combined fit of FC and PC (848 live days) plus UM (923 live days) plus SM (902 live days) from SuperK, with results as indicated, constraining the oscillation parameters to be roughly  $0.002 < \Delta m^2 / eV^2 < 0.006$  and  $0.85 < \sin^2(2\theta) < 1.0$ , with the fit minimum in the physical region at maximal mixing and  $0.0035 eV^2$ . The boundaries for MACRO and Soudan 2 are shown overlying the SuperK results in the right hand panel. One can see that the results of the largest instruments now reporting atmospheric neutrino data, water Cherenkov and two dissimilar tracking calorimeters, all agree on muon neutrino disappearance, and are consistent with oscillation between muon and tau neutrinos. I cannot do better than to quote Tony Mann from his 1999 Lepton-Photon conference plenary talk[20]: “I propose to you that congratulations are in order for the researchers of Kamiokande and of Super-K and more generally, for the non-accelerator underground physics community. For Fig. 1.23b, Ladies and Gen-

tlemen, is the portrait of a Discovery - the discovery of neutrino oscillations with two-state mixing.”



**Fig. 1.23.** a) (left): Allowed regions obtained by Super-K based upon  $\chi^2$  fitting to FC and PC single ring events, plus upward stopping muons, plus upward through-going muons. b) (right): Oscillation parameter allowed regions from Kamiokande (thin-line boundary), Super-K (thick-line boundary), MACRO (dashed boundaries), and Soudan 2 (dotted and dot-dashed boundaries). From Mann[20].

### 1.2.14 Long Baseline Results

The K2K experiment has been in operation for over one year at this writing. The 12  $GeV$  KEK proton synchrotron has been equipped with a neutrino line, and a double detector has been built at about 100  $M$  range, on the KEK campus. Neutrinos are aimed at the SuperK detector at a distance of 250  $km$ , and events have been recorded[58]. Note that a 1  $GeV$  neutrino would be near first minimum after 250  $km$  if the  $\Delta m^2 = 0.005 \text{ eV}^2$ .

At the time of this writing preliminary results are available, and it has been reported in conferences that the rate is low, consistent with the SuperK results, and inconsistent with no-oscillations at the  $2 \sigma$  level[59]. From the period of June 1999 through March 2000, the group received about  $1.7 \times 10^{19}$  protons on target (17% of proposal request), during the equivalent of about five months running. The events were easily extracted from a GPS synchronized 1.5  $\mu sec$  time window relative to the 12  $GeV$  KEK proton synchrotron fast beam spill (2.2  $sec$  repetition period and about  $5 \times 10^{12}$  protons on target per spill). During this run 17 associated events were collected in the SuperK 22.5 kiloton fiducial volume, when  $29.2 \pm 3.1$  were expected for no oscillations. The expected numbers are 19.3, 12.9 and 10.9 for  $3$ ,  $5$ , and  $7 \times 10^{-3} \text{ eV}^2$ . Of

these SuperK events, 10 are single ring, one of which is identified as electron-like (about equal to expectations).

Given the low energy of the neutrino beam ( $\sim 1 \text{ GeV}$ ), and frustratingly low data rate at SuperK probably not much more can be expected from this experiment than a simple confirmation of the SuperK atmospheric neutrino results. The full proposal-run would collect 174 or so events with no oscillations, and assuming oscillations, about half that. Of those, about half should be single ring muons, leaving perhaps 40-50 events from which to deduce the arriving neutrino spectrum. Given that the accelerator delivers beam about half a year each calendar year, one can see that it will take several years to achieve definitive results.

### 1.3 Implications

The ramifications of the explication of the atmospheric neutrino anomaly in terms of neutrino mixing and thus neutrino mass, are great and span the known realms of fundamental physics from large to small. We have not discussed in this chapter the links to solar neutrinos[49], nor the LSND results[50]. Certainly there is no conflict between the atmospheric muon neutrino results and the possible (nay likely) solar oscillations. If, however, both solar and the LSND results are correct, then we have surely some interesting physics to untangle, as it is generally admitted that no simple three neutrino model can incorporate all three neutrino anomalies, and that new degrees of freedom would be required (see Chapter IX). From the evidence presented in this chapter alone, however, we can make some far reaching, perhaps paradigm shifting, conclusions.

#### 1.3.1 Astrophysics and Cosmology

The implications of the oscillations results have been explored in other chapters in this book, so here we only outline those relative to the muon neutrino oscillations. First, it appears that neutrinos with summed masses of the order of  $0.1 \text{ eV}$  will not make any major contribution to resolving the dark matter quandary. Nonetheless with a ratio of 2 billion to one for photons (and neutrinos) to nucleons from the Big Bang, even such a small neutrino mass may be greater in total than all the visible stars in the sky. Hence while one must account for neutrino mass in further cosmological modeling, neutrinos are not likely to constitute the bulk of the “missing matter”. However if the neutrinos should be nearly degenerate in mass and all have masses in the range near  $1 \text{ eV}$  (and hence we are observing only small splittings with the oscillations), then neutrino mass may dominate the universe. While neutrinos are not favored by astrophysical modelers (fitting the spatial fluctuations in the cosmic microwave background for example), large neutrino masses are not ruled out ( $\Sigma M_i \leq 6 \text{ eV}$ ,  $H_o = 65 \text{ km/s/Mpc}$ ,  $i = 1, 2, 3$ )[51].



Nearly degenerate neutrino masses would not present a consistent picture with the quark and charged lepton masses, which make large mass jumps between generations. But who knows? We do not have a viable GUT with mass predictions[52], so an open mind is appropriate.

The other major area of significance, perhaps of the deepest significance, has to do with baryogenesis, the origin of the predominance of matter by one part per billion over anti-matter at Big Bang time. There are claims that the old idea of accumulation of net baryon number via CP violation in the quark sector, while satisfying the Sakharov conditions[53], may not suffice from the early stages of universe expansion[54]. If that is indeed the case, it may be that neutrinos provide the avenue for net baryon asymmetry generation, with the expression into hadrons becoming manifest relatively late in the game at electroweak phase transition[55]. CP and even CPT violation in the neutrino sector, as yet almost unconstrained, could have dramatic implications.

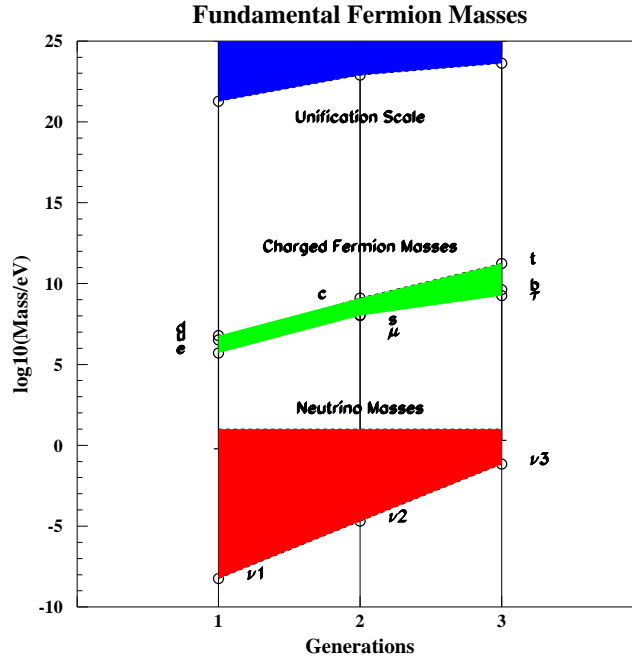
Neutrino masses and possible sterile neutrinos have also been invoked to help resolve problems in understanding heavy element synthesis in supernovae[56].

### 1.3.2 Theoretical Situation: Why So Important

Other chapters in this volume deal with the particle theory situation, so we make only several general remarks here, more from the experimentalists' phenomenological viewpoint. Figure 1.24, shows the masses of the fundamental fermions in three generations on a logarithmic scale in mass. Dramatically, one sees that if the neutrino masses are near the lower bounds (that is at the presumed mass differences from present atmospheric and solar results), they lie 10-15 orders of magnitude below the other fundamental fermions (charged quarks and leptons). Graphically one notes the spacing between the neutrino masses and the charged fermion masses is just about the same as the distance (on the log scale) to the unification scale. This is a pictorial representation of the see-saw mechanism, as noted more than ten years ago[16]. This points up the task for grand unification model building, and highlights the deep link between neutrino masses and nucleon decay[52].

### 1.3.3 Future Muon Neutrino Experiments

The physics community seems to have rapidly accepted, with caution, the seeming inevitability of neutrino mass and oscillations[44]. Yet most probably the game has hardly begun and many a subtlety may await our exploration. However if the LSND claims will go quietly away (after the BOONE experiment runs), the mass and mixing picture could settle into the simple hierarchical pattern as explored in the bi-maximal mixing scenario (or similar versions). This highlights the importance of experiments to follow up on the LSND results as one of the first agenda items in the current neutrino business (see Chapter VII).



**Fig. 1.24.** The masses of the fundamental fermions. The lower shaded region indicates the rough range allowed by present oscillations results, with the upper boundary for nearly degenerate neutrino masses and lower bound for approximate atmospheric and solar results with an extrapolation to the first generation mass. The unification scale marks the rough range implied by the see-saw mechanism.

Given present indications, it would seem that the K2K[58], MINOS[60] and CERN-Gran-Sasso experiments ICANOE[61] and OPERA[62] should confirm the SuperK results and make the oscillation parameters more precise. Of course, one would really like to see tau appearance, not just muon disappearance to be sure we are not being misled. There has been some debate in the community as to what constitutes appearance. Because of the complexity of tau final state identification, this author would prefer to see a real tau track recorded. In any case plans are in progress in the US, Japan and Europe for the obvious follow up experiments to solidify the oscillation scenario and refine the parameters, which experiments should take less than a decade. At this time it appears that only OPERA has the opportunity to record physical tau lepton tracks in emulsions, though the other experiments (including SuperK) may be able to detect tau kinematic signatures statistically.

More interesting for the long range physics is filling in the MNS matrix (lepton equivalent of quark CKM matrix) for neutrinos[63]. This is not an easy business. The atmospheric neutrino measurements really are only

defining, at best, three of the nine elements! Solar neutrinos get us another, perhaps a constraint on two. Measuring the tau related components directly seems pretty hopeless. Of course if we can assume the matrix to be unitary and real we would be in good shape as there are then only three independent parameters (plus the masses). But we do not know this, and if there exist CP violations we then have a total of three angles and one phase plus possibly another phase for the case of Majorana neutrinos, but which phase is only measurable in special circumstances such as neutrino-less double-beta-decay. If there are more (heavy or sterile) neutrinos, then things could be much more complicated (as the 3 by 3 sub-matrix will not be unitary). By analogy with the quarks (where the 3 by 3 CKM matrix with small mixing angles and one CP violating phase suffices), perhaps we should not worry too much, except for lack of any guidance whatsoever from theory. CP violation is only very weakly constrained experimentally in the neutrino sector at present, so we could be in for big surprises, and given the neutrino connection with cosmology and baryogenesis, one should indeed be suspicious, I believe.

As a whole, the particle physics community is just beginning to examine the newly illuminated possibilities in the neutrino sector. At the moment it appears as though muon colliders may provide our best route for next generation explorations in this realm[64,65]. The serendipitous realization that muon storage rings can provide neutrino beams more intense by about 4 orders of magnitude than previous artificial neutrino sources, along with the potential, via polarization of these beams, to make nearly pure beams of muon neutrinos or anti-neutrinos, with a relatively narrow energy spread, allows one to dream of experiments not heretofore thought possible. The prospects for this endeavor are just emerging at the time of this writing and the dialog between physics possibilities and machine technical capabilities is in much ferment. The present excitement about this endeavor, probably at least ten years from realization, promises much evolution of thinking about critical tests and experiment planning. Aside from simple checking of previous results, precision measurement of oscillation parameters, and filling out of the MNS matrix, the major goal in this authors mind is exploration for CP and CPT violation in the neutrino sector, not possible by any other means yet conceived. Of course if  $\theta_{13}$  turns out to be zero, which hopefully we will know in a few years, then CP violation is not possible. Credibly motivated CPT violation can still be a possibility however[67].

Table 1.2 shows a rough comparison of the physics capabilities and reach of SuperK and the various present and future long-base-line experiments. This table was generated by an informal working group at the 2000 Aspen “Neutrinos with Mass” Workshop. Although the details may annoy proponents of some projects (and please others), the purpose was not to evaluate specific experiments, but to try and gauge the strengths of the various approaches as we move forward in the quest to complete the MNS matrix and explore for CP and CPT violations in the neutrino sector. We had inadequate

information about OPERA and the proposed 50 GeV proton driven neutrino beam in Japan (JHF to SuperK), so they may not be fairly represented.

The table assumes that the  $\Delta m^2 = 0.003 \text{ eV}^2$  and  $\sin^2(2\theta) \simeq 1.0$  with dominantly  $\nu_\mu \leftrightarrow \nu_\tau$  mixing, large mixing angle MSW solar neutrino oscillations and no LSND/BooNE indication of oscillations. We also assumed a 20 – 50 GeV neutrino factory and high quality neutrino detector at a few thousand kilometers distance.

There was considerable discussion of whether the new experiments will or will not be able to see at least one dip in the detected neutrino spectrum, unambiguously discriminating oscillations from disappearance (as in decay). My conclusion is that such a detection will be very difficult for all experiments with traditional neutrino beams if the  $\Delta m^2$  is at the low end of the allowed region. ICANOE claims to be able to detect oscillations in the cosmic ray beam, a consequence of their excellent resolution and the larger range of  $L/E$  values available from the atmospheric neutrinos than from a fixed distance long-base-line beam.

I think what we all learned from this exercise is that there really is a great gulf between what we can accomplish with a neutrino factory and anything prior to that, even with more powerful traditional neutrino beams.

**Table 1.2.** Comparison of SuperK and long-base-line neutrino experiments in terms of physics capabilities and reach. See text for explanation.

Experiment:	SuperK (atm $\nu$ )	K2K	MINOS	ICANOE	OPERA	JHF2K	$\nu$ Fac
$d(\ln(\Delta m^2))$	50%	20%	10%	10%	20%	10%	2%
$d(\sin^2 2\theta)$	5%	5%	5%	5%	?	4%	2%
See Oscillations?	×	×	$\sqrt{(?)}$	$\times(\text{atm}\sqrt{?})$	?	×	$\sqrt{?}$
$\tau$ appear (kink)	×	×	×	×	$\sqrt{?}$	×	$\sqrt{?}$
$\tau$ appear (kinem)	$\sqrt{?}$	×	$2\sqrt{?}$	$3\sqrt{?}$	$4\sqrt{?}$	×	$4\sqrt{?}$
$\sin^2 2\theta_{13}$ limit	0.1	0.03?	0.03	0.015	(ident e?)	0.03	$1 - 3 \times 10^{-3}$
$d(\nu_s/n_\tau)$	20%	×	5%?	5%	?	×	1%
Elim Decay Models?	$\times(? \text{ NC/CC})$	×	$\sqrt{(\text{NC/CC})}$	$\times(\text{atm}\sqrt{?})$	?	×	$\sqrt{?}$
Sign of $\Delta m^2$	×	×	×	×	×	×	$\sqrt{?}$
$\nu_e \rightarrow \nu_\tau$	×	×	×	×	×	×	$\sqrt{?}$
CP violation tests	×	×	×	×	×	×	$\sqrt{?}$
CPT violation tests	×	$\times(?)$	$\sqrt{?}$	$\sqrt{?}$	×	$\times(?)$	$\sqrt{?}$

Measuring absolute neutrino mass remains a frustrating problem, which will not be resolved in the near future it seems. While pushing to lower mass limits with Tritium beta decay experiments will apparently not be able to reach below 0.1 eV, there is some hope from CMBR measurements[51], there is a long shot via the “Weiler process”[66], and optimistically neutrino-less double-beta-decay experiments may eventually reach 0.01 or even 0.001 eV.

At high energies, explorations for cosmic neutrinos may be carried out in deep arrays in the ocean and under ice[68]. While the main goal of these attempts at high energy neutrino astronomy will be aimed at astrophysics, with a high-energy-threshold-detector capable of registering neutrinos in the  $PeV$  range, it may be that such instruments will be able to directly detect tau neutrinos (via the “double bang” signature[69]), and even determine the neutrino flavor mix, to the benefit of both particle physics and astrophysics.

A next generation (megaton) scale nucleon decay instrument to probe lifetimes to  $10^{35}$  years would do wonders for advancing neutrino physics as well. Simply building a larger version of SuperK will not suffice because of the need for greater resolution as well as size. The only candidate I see to go beyond SuperK is something like the AQUA-Rich style of imaging water Cherenkov detector[35,36]. An attractive alternative which need not be so massive to get to  $10^{35}$  years in kaon modes of nucleon decay, might be a 50 – 70 *kiloton* liquid argon detector of the ICARUS style. Perhaps such a detector can be realized in concert with a long baseline beam from a neutrino factory.

From the foregoing it should be apparent that we have entered a new era in elementary particle physics, and that one can expect a long and interesting exploration into neutrino mass and mixing now that the door has been opened.

## Acknowledgments

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## Appendix: Super-Kamiokande Collaboration, 6/00

**Boston U.** M. Earl, A. Habig, E. Kearns, M.D. Messier, K. Scholberg,  
 J.L. Stone, L.R. Sulak, C.W. Walter  
**Brookhaven Nat. Lab.** M. Goldhaber  
**U. of Cal., Irvine** T. Barszczak, D. Casper, W. Gajewski, W.R. Kropp,  
 S. Mine, L.R. Price, M. Smy, H.W. Sobel, M.R. Vagins  
**Cal. State U., Dominguez Hills** K.S. Ganezer, W.E. Keig  
**George Mason U.** R.W. Ellsworth  
**Gifu U.** S. Tasaka  
**U. of Hawaii, Manoa** A. Kibayashi, J.G. Learned, S. Matsuno, D. Take-  
 mori  
**Inst. of Part. and Nuc. Stud., KEK** Y. Hayato, T. Ishii, T. Kobayashi,  
 K. Nakamura, Y. Oyama, A. Sakai, M. Sakuda, O. Sasaki  
**Kobe U.** S. Echigo, M. Kohama, A.T. Suzuki  
**Kyoto U.** T. Inagaki, K. Nishikawa  
**Los Alamos Nat. Lab.** T.J. Haines  
**Louisiana State U.** E. Blaufuss, B.K. Kim, R. Sanford, R. Svoboda  
**U. of Maryland** M.L. Chen, J.A. Goodman, G. Guillian, G.W. Sullivan  
**State U. of N.Y., Stony Brook** J. Hill, C.K. Jung, K. Martens, M. Malek,  
 C. Mauger, C. McGrew, E. Sharkey, B. Viren, C. Yanagisawa  
**Niigata U.** M. Kirisawa, S. Inaba, C. Mitsuda, K. Miyano, H. Okazawa,  
 C. Saji, M. Takahashi, M. Takahata  
**Osaka U.** Y. Nagashima, K. Nitta, M. Takita, M. Yoshida  
**Seoul Nat. U.** S.B. Kim  
**Tohoku U.** M. Etoh, Y. Gando, T. Hasegawa, K. Inoue, K. Ishihara,  
 T. Maruyama, J. Shirai, A. Suzuki  
**U. of Tokyo** M. Koshiba  
**Inst. for Cos. Ray Res., U. of Tokyo** S. Fukuda, Y. Fukuda, M. Ishit-  
 suka, Y. Itow, T. Kajita, J. Kameda, K. Kaneyuki, K. Kobayashi, Y. Kobayashi,  
 Y. Koshio, M. Miura, S. Moriyama, M. Nakahata, S. Nakayama, Y. Obayashi,  
 A. Okada, K. Okumura, N. Sakurai, M. Shiozawa, Y. Suzuki, H. Takeuchi,  
 Y. Takeuchi, T. Toshito, Y. Totsuka (Spokesman), S. Yamada  
**Tokai U.** Y. Hatakeyama, Y. Ichikawa, M. Koike, K. Nishijima

**Tokyo Inst. for Tech.** H. Fujiyasu, H. Ishino, M. Morii, Y. Watanabe

**Warsaw U.** U. Golebiewska, D. Kielczewska

**U. of Washington, Seattle** S.C. Boyd, A.L. Stachyra, R.J. Wilkes,  
K.K. Young